

DSN Transient Observatory

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The DSN Transient Observatory (DTO) is a signal processing facility that can monitor up to four DSN downlink bands for astronomically interesting signals. The monitoring is done commensally with reception of deep space mission telemetry. The initial signal processing is done with two CASPER¹ ROACH1 boards, each handling one or two baseband signals. Each ROACH1 has a 10 GBe interface with a GPU-equipped Debian Linux workstation for additional processing. The initial science programs include monitoring Mars for electrostatic discharges, radio spectral lines, searches for fast radio bursts and pulsars and SETI. The facility will be available to the scientific community through a peer review process.

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1. Introduction

The NASA Deep Space Network (DSN) is a world-wide facility for communicating with deep space missions. Transient Observatory (DTO) is a signal processing facility that can monitor up to four DSN telemetry bands for astronomically interesting signals. Since telemetry signals occupy only a small fraction of the entire band, the rest of the band can be used for commensal scientific investigations. The signal processing requirements may be quite different for these projects. DTO supports these by using different firmware on the same platform.

Currently, the primary scientific objective is monitoring Mars for electrostatic discharges. Such bursts, reported by Ruf *et al.* (2009), occurred during a convective dust storm. Since the DSN is receiving data from spacecraft at Mars almost continuously, a statistically significant database can reveal the conditions which give rise to such events. Other planets can also be monitored for transient phenomena.

Additional investigations include searching for astronomical transients such as fast radio burts (FRBs), pulsars and signals resulting from extraterrestrial technologies.

There is one 70m diameter antenna in Goldstone, California, with others near Canberra, Australia, and Madrid, Spain, roughly equidistant in longitude to enable continuous communication with robotic missions exploring the Solar System. Each site also has at least three 34-m antennas. Table 1 shows the bands used for deep space to Earth communications.

The initial signal processing is done with two ROACH1² boards, each handling up to two 640MHz-wide baseband signals. Each ROACH1 has a 10 GB ethernet (10 GBe) interface with a GPU-equipped Debian Linux workstation for additional processing. The monitoring is done commensally with reception of deep space mission signals.

Since deep space missions move slowly across the sky, the time for acquiring data from a given direction can be quite long, though the direction is not under the investigator's control. At minimum elongation, Venus moves about one beamwidth per hour at X-band for a 70m antenna or at Ka-band for a 34m

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¹Collaboration for Astronomy Signal Processing and Electronics Research

²Reconfigurable Open Architecture Computing Hardware, model 1

Table 1. Deep space to earth communication bands used by the DSN.

Band	Frequencies (GHz)	Bandwidth (MHz)	Polarization
S	2.265 - 2.305	40	LCP RCP
X	8.25 - 8.65	400	LCP & RCP
Ka	31.85 - 32.25	400	LCP & RCP

^a The polarization for S-band is configured at the beginning of a tracking session. It is normally RCP.

^b Only some 34-m antennas have S-band.

antenna. For Mars the minimum dwell time is about 100 min. For Jupiter and Saturn it is about $5\frac{1}{2}$ and 11 hr respectively. If, on the other hand, one wishes to survey more sky quickly, for a 34m antenna that is not moving, the dwell time for a position on the sky is ~ 50 s at S-band, ~ 14 s at X-band and 3.8s at Ka-band. A non-tracking 34-m antenna can cover 1% of the sky in 17 earth rotations at S-band, 59 at X and 227 at Ka.

DTO can also be used during tracking sessions assigned to observations of radio astronomical sources. The facility will be available to the astronomical community through a peer-reviewed proposal process.

2. Hardware

Figure 1 shows an overview of the signal processing facility. A commercial 24×4 intermediate frequency (IF)

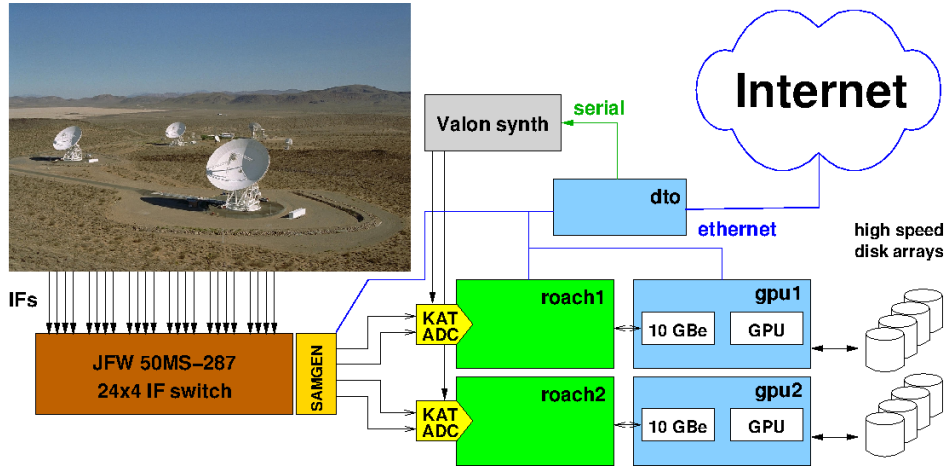


Fig. 1. Overview of the DSN Transient Observatory.

matrix switch made by JFW Industries, Inc., directs up to four station IFs to the inputs of two ROACH1 signal acquisition and processing units. Two high-speed, multi-core, GPU³-equipped workstations accept processed data from each ROACH over a 10 Gb ethernet (10GbE) port.

The PowerPCs on the ROACH boards boot their kernel images from the master controller `dto`. `dto` also has the file systems of the PowerPCs which control the operation of a Xilinx XC5VSX95T field programmable gate array (FPGA). The bit-files which configure the ROACH FPGAs are loaded by the PowerPCs. So, in effect, `dto` provides the firmware for the FPGAs, allowing rapid switching of firmware under computer control.

³graphics processing units

The Sample Clock Generator (SamGen) subsystem provides the clock signals for the analog-to-digital converters (ADC), optional synchronization pulses and IF amplification and low-pass filtering. Figure 2 has a schematic diagram. SamGen has a Valon dual synthesizer so the two ROACH board ADCs can be

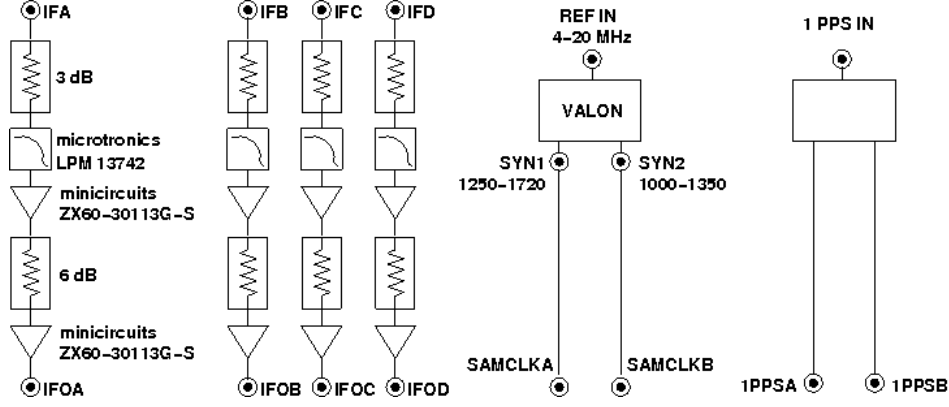


Fig. 2. Schematic diagram of the sampler clock and IF distribution chassis.

independently clocked. It also distributes 1pps synchronization pulses to the KAT ADCs.

In addition to the controller `dto` and the two PPCs, there are two high-performance computers. Each post-processing PPC has two Intel Westmere 2.66GHz X5650 processors with six cores, allowing it to run twelve threads. It has 96 GB of RAM, two GTX 580 GPU processors each with 512 cores, and 48TB of fast disk. 32T are available for data storage. All hosts have the Debian Linux operating system.

3. Firmware

3.1. Kurtosis Spectrometer

On 2006 June 8 Deep Space Station 13 (DSS-13) detected non-thermal bursty emissions from Mars (Ruf *et al.*, 2009) that showed resonances similar to Schumann resonances on Earth (Schumann, 1952). Transient non-thermal radio bursts can be distinguished from Gaussian thermal noise by computing the kurtosis (normalized fourth moment) of the signal voltage (Ruf *et al.*, 2006). For such studies we have designed specifically for DTO a 1024-ch firmware spectrometer that computes kurtosis as well as power. The design is shown in Figure 3. For Mars, the integration time for these calculations, a parameter which can be adjusted, is 1 ms. This allows a signal kurtosis spectrogram to be examined for the presence of modulation by very low frequency waves propagating between the surface and ionosphere of Mars. The DSN has telemetry with at least one spacecraft at Mars for an average of 20 hrs every day. One of DTO's main goals is to monitor Mars diligently for further evidence for electrostatic discharges.

3.2. High Resolution Spectrometer

It would be unlikely to detect radio spectral line emission from an arbitrary direction in the sky but planetary atmospheres can produce such emission from very low density upper atmospheres (Gulkis *et al.*, 1978; Wilson *et al.*, 1981). One of the available firmwares is a 32K-channel spectrometer. It was developed for the Tidbinbilla AGN Maser Survey (TAMS) project led by Harvard Smithsonian Astrophysical Observatory (Zaw *et al.*, 2014) and is part of the 17-27 GHz receiver system on DSS-43 (Kuiper *et al.*, 2016). With a 640 MHz bandwidth this gives a spectral resolution of 20 kHz. The Doppler velocity resolution is 2.5 km s^{-1} at S-band, 0.7 at X-band and 0.2 km s^{-1} at Ka-band. This firmware is most likely to be used for antenna time assigned to astronomical research. It would also be useful for monitoring radio frequency interference (RFI) and spacecraft transmitters which have lost lock and drifted in frequency.

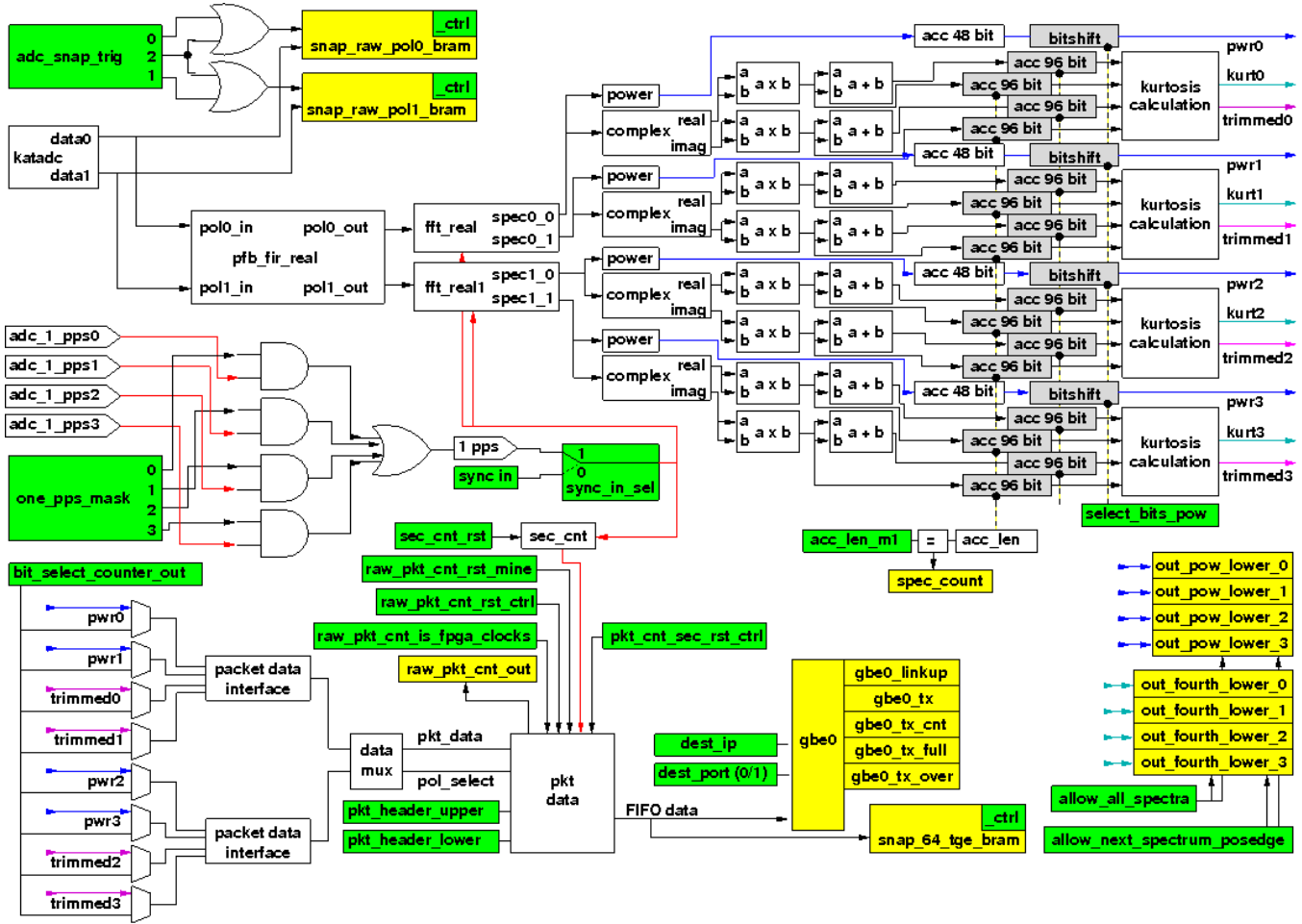


Fig. 3. Schematic diagram of the kurtosis spectrometer firmware, including all the registers and data stores.

3.3. SETI Spectrometer

Extraterrestrial civilizations that are located close to the Sun's ecliptic plane could be aware of Earth and its life-supporting potential from Earth's transits across the Sun. Such a civilization might direct a beacon towards Earth to initiate possible contact. An interesting strategy is to conduct searches for extraterrestrial civilizations (SETI) along the ecliptic plane (Henry et al., 2008). The DSN, in communication with spacecraft at or travelling towards other planets, has many antennas pointed close to the ecliptic. A commensal SETI search may have enhanced chances of success compared to similar searches at radio observatories (Werthimer et al., 2001). There are 82 K and G stars within one kpc of Earth within this zone (Heller & Pudritz, 2016), so that over a time comparable to the orbital periods of the planets, they would be within the beam of antennas communicating with deep space missions.

Amplitude modulated signals transmitted by putative extraterrestrial civilizations are expected to be most easily detected by the carrier tone, which is expected to be extremely narrow. An extremely high resolution spectrometer design, SERENDIP VI⁴, will be adapted from ROACH2. The firmware performs 4K channelization. The samples from each channel of the firmware output are further channelized in software using GPUs. A 128K PFB on each channel from the firmware spectrometer will yield a spectral resolution of 1.2 Hz. SERENDIP VI has been implemented in SETIBURST, a multi-purpose signal processor (Chennamangalam et al., 2016) similar in concept to DTO.

The high resolution of the final spectra allows masking of spacecraft telemetry and known interference

⁴[//casper.berkeley.edu/wiki/SETI/FRB_Spectrometer_\(SERENDIP_VI\)](http://casper.berkeley.edu/wiki/SETI/FRB_Spectrometer_(SERENDIP_VI))

signals. Since the amount of data is still huge, additional back-end processing will decimate the data. For example, the JPL “setispec” used in the GAVRT SETI project⁵ (Jones et al., 2010), reports for each of 4096 coarse channels, the number of and power detected in the strongest high-resolution sub-channel.

4. Software

4.1. Monitor and Control

The monitor and control (M&C) software has a server/client architecture. All control software is written in Python. Inter-process communication (IPC) is managed with Pyro⁶.

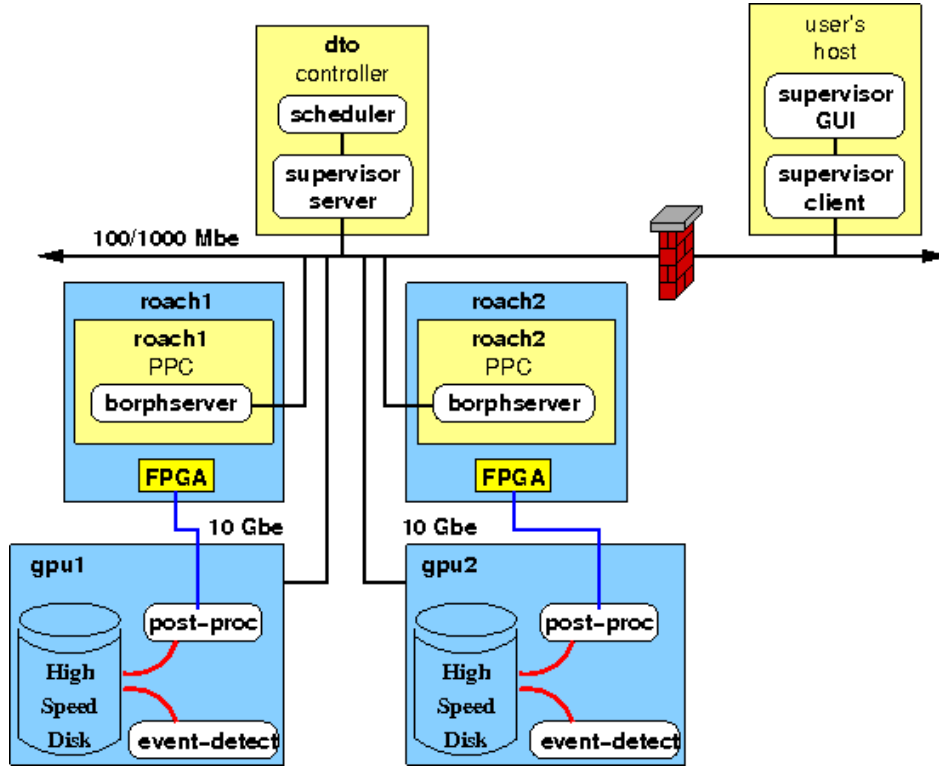


Fig. 4. Overview of the DTO software.

Figure 4 gives a schematic overview of the software. The **scheduler** processes the DSN 7-Day Schedule for the Goldstone antennas and selects antennas and frequency bands according to a rule set determined by the science team.

The **supervisor** is a client of the hardware servers and monitors and controls all aspects of DTO – the state of the IF switches, the frequency and power of the sample clock generators, the gain of the KATADC RF sections, the firmware loaded into the FPGAs, etc. It also collects metadata from the station’s monitor data server using the DSN’s IPC protocol.

The can be overseen by a human through the supervisor client. This has a set of classes and functions through which an expert user can communicate with the supervisor through a Python command line. A graphical user interface (GUI) can invoke the same classes and functions to provide a more convenient overview.

The **ROACH Power PCs** control most of the ROACH operation. The PPC filesystems are on dto. The supervisor loads the appropriate firmware for a session into the ROACHs.

⁵<http://galileo.gavrt.org/seti/>

⁶<http://pythonhosted.org/Pyro4/>

The user's client software works through a tunnel (Kuiper *et al.*, 2012) which is created by a user with the requisite authority (username and two-factor passcode) to log in to the firewall's gateway. Only one log-in is needed for a session.

4.2. *Post-Processing*

Data generated by the firmware streams through 10GbE connections to the signal processing hosts. Because of the generally high data rate involved, this software is normally written multi-threaded C. Python's libraries for GPU support are being investigated. The output is written to disk for further real-time analysis.

In the final software, the data are stored temporarily in a circular buffer. These data are examined for "events". This software is the most complex as it must separate real from false events, generate alerts for events requiring prompt attention and store data which events of interest.

5. Status and Conclusion

DTO is awaiting shipment to the Goldstone Deep Space Communications Complex (GDSCC). The hardware, firmware and M&C software for the initial science program has been verified in the laboratory at JPL. The location and access to power and signals at Goldstone have been assigned. Paperwork required for installation in the configuration-controlled DSN operations environment has been completed. DTO will become operational at Goldstone in the late summer of 2016.

DTO will be operated as an open facility. The JPL Interplanetary Network Directorate (IND) which manages the DSN will accept proposals from outside investigators who bring their own firmware to conduct research with different goals.

6. Future Work

Because of the flexibility built into the CASPER development ecosystem, DTO should not be considered limited to the applications described here, but rather a prototype for general purpose commensal science signal processing. For example, the high resolution spectrometer design was recently implemented as four spectrometers on a single ROACH2. Additional modifications, such as extending the kurtosis based designs for flexible integration times, and development of higher order (6th, 8th moment) statistics are also ongoing.

The Instituto Nacional de Técnica Aeroespacial (INTA) and Ingeniera de Sistemas para la Defensa de España (ISDEFE) have made available four ROACH1 boards together with a controller host to the Radio Astronomy Department of the Madrid Deep Space Communications Complex (MDSCC). INTA and JPL will collaborate in assembling a second DTO for MDSCC which will be operated by INTA scientists.

A fifth ROACH1 board will be used to provide a spectrometer for the PARTNeR educational antenna (Proyecto Académico del RadioTelescopio de NASA en Robledo), a project also managed by INTA.

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